

Review

Sustainable Approach and Safe Use of Biochar and Its Possible Consequences

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Abstract: Biochar is considered as a potential substitute for soil organic matter (SOM). Considering the importance of biochar, the present review is based on the different benefits and potential risks of the application of biochar to the soil. Biochar addition to low organic carbon soils can act as a feasible solution to keep soil biologically active for the cycling of different nutrients. The application of biochar could improve soil fertility, increase crop yield, enhance plant growth and microbial abundance, and immobilize different contaminants in the soil. It could also be helpful in carbon sequestration and the return of carbon stock back to the soil in partially combusted form. Due to the large surface area of biochar, which generally depends upon the types of feedstock and pyrolysis conditions, it helps to reduce the leaching of fertilizers from the soil and supplies additional nutrients to growing crops. However, biochar may have some adverse effects due to emissions during the pyrolysis process, but it exerts a positive priming effect (a phenomenon in which subjection to one stimulus positively influences subsequent stimulus) on SOM decomposition, depletion of nutrients (macro- and micro-) via strong adsorption, and impact on soil physicochemical properties. In view of the above importance and limitations, all possible issues related to biochar application should be considered. The review presents extensive detailed information on the sustainable approach for the environmental use of biochar and its limitations.

Keywords: carbonaceous sorbent; contaminants; human health; nutrients; pyrolysis; soil properties

1. Introduction

Biochar is a dark-black-colored, partially combusted (pyrolyzed), and recalcitrant compound which helps to enrich the nutrient balance and carbon stock in the soil [1–3]. It is a porous carbonaceous sorbent generally produced from materials of biological origin (crops residues) which is formed after specific thermochemical conversions (pyrolysis) under limited oxygen supply conditions. Most frequently, biochar is a product of plant and agricultural residues derived biomass carrying oxygen-containing functional and aromatic groups [4]. It has physicochemical properties which allow it to be used for a long time, safely accumulate carbon in the environment, and improve soil health [5–7].

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The pyrolysis of biomass occurs by producing three co-products: char, gas, and oils. The pyrolysis conditions such as temperature, pressure, residence time, and feedstock types are the main factors governing each fraction's relative amounts and characteristics [8]. For example, slow pyrolysis, based on a lower temperature and a longer residence time than fast pyrolysis, typically yields 35% char, 35% gas, and 30% liquid [9]. Biochar could improve soil structure, reduce greenhouse gas emissions such as nitrous oxide and methane from the soil, and decrease the leaching of chemicals to groundwater.

Various mechanisms have been proposed that increase the nutrient availability to plants in different ecosystems. Among these mechanisms are the incorporation of biochar containing soluble nutrients [10]; the reduction in nutrient leaching because of the physicochemical properties of biochar [11]; and minimizing N loss by the volatilization of NH_3 and the denitrification of N_2 and N_2O [12]. Other mechanisms include the mineralization of biochar labile fraction, which has organically bound elements [13], and the cumulative retention of N, P, and S, which is connected with enhancement of biological activity [14]. There is a huge stock of literature dedicated to biochar testing results on almost all types of soils. Most of these findings conclude that biochar can serve as an excellent soil amendment [15,16]. However, this amendment's actual effect depends on the type of biochar, the production conditions, the soil condition, and the amount of biochar applied [17,18].

Biochar carries properties that enhance the remediation process of contaminated soils [19,20]. It has a large, negatively charged internal surface area, which is resistant to degradation. The higher the pyrolysis temperature is, the higher the surface area of the produced biochar is [21], although this effect has its limits due to the excessive burning of carbon structures, e.g., at extremely high pyrolysis temperatures, the pores of biochar collapse and surface area decreases [22]. The biochar having a negative electrical charge on the internal surface acts as the cation exchange resin that attracts metal cations from the soil solution [23]. Thus, the concentration of metal and organic contaminants present in soil could be reduced effectively [24] along with the reduced bioavailability of contaminants to plants and soil organisms [25]. The recalcitrant property of biochar provides its carbon sequestration potential, and the biochar is effective at releasing the carbon slowly over a very long period. The same properties help biochar to slowly release the mineral nutrients [26,27]. Although biochar has a high degree of resistance, it can still be mineralized gradually to CO_2 , and soil organic matter would prevail by applying biochar over a long period of time due to its recalcitrant properties [28,29]. Biochar is not a homogenous product [30]. It consists of numerous fractions and pools which are decomposed in the soil at different rates. Various types of biochars are produced that show different physicochemical properties and functional performance. This variability is possible because of changes in pyrolysis conditions (temperature, heating rate, the vapor residence time) and variable types of feedstocks used [31,32].

The application of biochar to soil was found to be helpful in improving the fertility status [33,34]. Solid digestate generated in anaerobic digestion is a potential feed stock for preparing biochar, which is beneficial in improving and sustaining soil fertility while building high soil organic matter and the long-term release of micronutrients as compared to the fertilizers available in the market [35]. The present review deals with the effects of feedstock and pyrolysis conditions on biochar production and detailed characterization of this soil amendment. It also critically analyzes the potential benefits of biochar applications as a soil ameliorant, adsorbent, and bioremediation agent, as well as other environmental implications and possible risks to the environment and human health.

2. Pyrolysis Process

The properties of biochar are governed by the type of feedstock and the rate of pyrolysis. The thermal decomposition of organic matter in the process of pyrolysis takes place in the absence of oxygen or under depleted oxygen conditions (Figure 1). The quality of biochar mainly depends on the temperature that is applied during the pyrolysis process. The product generated from pyrolysis contains char, bio-oil, and synthetic gases, and the

ratio of generated products depends upon the type of pyrolysis. It was concluded that the higher the pyrolysis temperature, the higher the biochar carbon content will vary from 45.5 to 64.5%, along with the decrease in oxygen content [36]. With the increase in pyrolysis temperature, the oxygen content decreases, and the nitrogen content of biochar increases only up to the certain temperature. A relative increase in nitrogen content proposes that raising the temperature conserves biochar nitrogen. The incorporation of nitrogen in the biochar structures make it resistant to heating, and its volatilization become difficult, as suggested by Gaskin [37]. The C content was higher with increasing pyrolysis temperatures from 300 to 800 °C. The increase in carbon content with the increasing temperature, owing to the release of volatiles throughout pyrolysis, leads to the elimination of non-carbon species and thus carbon enrichment. Another study reported that N and H contents were decreased, which may be due to volatilization loss [38]. The nitrogen will be volatilized or conserved depending on the tenacity of the bond between the carbon and nitrogen in the feedstock material. The increase in temperature leads to a reduction in C sequestration efficiency because a large part of C is wholly burned [39].

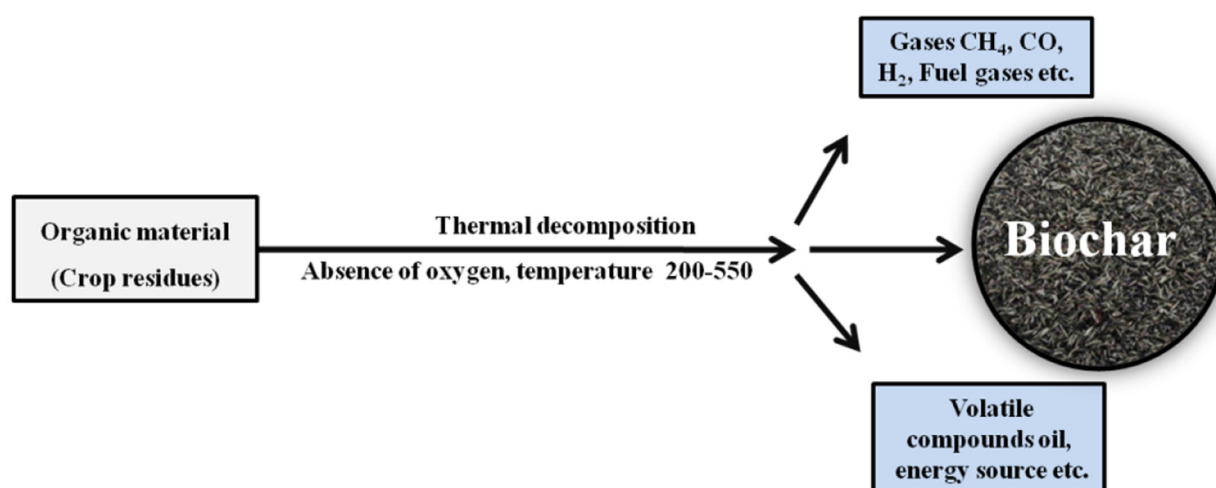


Figure 1. Biochar production technique from organic material (crop residue).

The pyrolysis process is the main function significantly responsible for biochar's properties and quality. During the traditional biochar preparation generally adopted by farmers, the feedstock is burned under anaerobic conditions. The scientific biochar preparation used to convert biomass into renewable energy products is divided into four categories. The class is based upon the temperature, the heating rate, and the residues type [40]. These classes are (a) slow pyrolysis, (b) fast pyrolysis, (c) flash pyrolysis, and (d) gasification. The maximum char yield can be up to 30–35% obtained by the slow pyrolysis. The vapor residence time may range from 5 to 30 min, and the pyrolysis temperature ranged from 300 to 700 °C. The C content of biochar is mainly governed by the heating rate and the temperature applied in the pyrolysis process. The pyrolysis is mainly influenced by the type and nature of stock along with rate of temperature applied. The composition and amount of biochar is also influenced by the material introduced for the biochar's preparation. It has been reported that the C content increased with pyrolysis temperature only up to 300 to 800 °C [39]. Among these processes, only slow and fast pyrolysis are primarily used for making biochar, and the resulting properties of the produced sorbent largely depend on temperature, pyrolysis time and heating rate [41,42]. In addition, there is also a separate process of the hydrothermal carbonization, resulting in the production of hydrochar.

2.1. Slow and Fast Pyrolysis and Hydrothermal Carbonization

Slow pyrolysis is a process in which the biomass is heated slowly in the absence of oxygen. Slow pyrolysis often results in an increase of biochar yield and decreased carbonized fraction of biochar, i.e., biochar carbon content is inversely related to biochar yield [43]. More highly aromatic biochar is produced using slow pyrolysis than in fast pyrolysis. However, fused aromatic ring compound sizes in slow and fast pyrolysis chars were similar (around 7–8 rings per compound). Fast pyrolysis is another technique for biochar production. The feedstock for fast pyrolysis should contain less than 10 wt. % moisture. The temperature here rises very quickly up to 400–500 °C, while vapor residence times range from 1 to 5 s [44]. Hydrothermal carbonization is based on biomass heating at very high temperature and pressure underwater, resulting in charred water slurry [45]. The resulting product is termed as ‘hydrochar’ and is related to biochar as a biomass-derived carbonaceous material. The solid char produced is easily separated from other byproducts. Hydrochars can be used for the remediation of contaminated soil and water [46]. The chemical nature of biochar from the pyrolysis point of view is different from that of the hydrochar. Hydrochars are less stable than biochars and are generally dominated by alkyl moieties, whereas biochars are rich in aromatic moieties.

2.2. Stages of Pyrolysis

Pyrolysis covers different complex reactions at the time of thermal conversion. These reactions are condensation, polymerization, dehydration, dehydrogenation, deoxygenation, and decarboxylation, making the process very complex [47]. Lignin and cellulose are major components of crop residues. The cellulose and hemicellulose components of biomass (60–75%) start to decompose at a temperature of 200–400 °C, while lignin (15–25%) degrades around 300 to 700 °C [48]. There are two main steps of the pyrolysis process. The initial step is devolatilization, consisting of several reactions such as dehydration, dehydrogenation, and the decarboxylation reaction. The last step is known as cracking, which involves the final decomposition reactions between the volatiles generated and the carbonaceous remains [49]. Two stages of decomposition during pyrolysis are also confirmed by the thermogravimetric analysis (TGA) of biomass [50,51]. Weight loss in biomass starts at the temperature of 100 °C because of moisture release. At temperatures of around 200–300 °C and 300–400 °C, the degradation of hemicellulosic and cellulosic components starts, which is the second significant mass loss stage [50]. Char produced in this stage is rich in lignocellulosic compounds that are further decomposed as the temperature rises above 400 °C. The resulting biochar is rich in volatiles along with a lower char yield [48].

3. Feedstock for Biochar Production

Along with plant biomass, other organic materials, such as poultry litter and sewage sludge, can also produce biochar using pyrolysis, and this was proposed as an alternative way of managing different organic wastes [52,53]. The properties of biochar vary largely depending on the type of feedstock used. If the content of lignocellulosic material in the feedstock is high, it gives a higher biochar yield because lignin is transformed into char during the pyrolysis process [54].

The feedstock materials used for biochar production differ largely in chemical composition and the content of mineral nutrients (Table 1). The potassium content in raw material can influence the final biochar pH, while the C:N ratio is important not only for the nitrogen content but also for phosphorus availability. A recent meta-analysis has shown that biochar produced from low C:N ratio feedstock materials effectively enhance phosphorus availability [55].

Table 1. Chemical composition (g kg^{−1}) and pH of different biochar feedstock.

Raw Material Used for Biochar Preparation	pH	C	N	P	K	Production Temperature, °C	Remarks	References
Bark (<i>Acacia mangium</i>)	7.4	398	10.4	-	-	260–360	Made of wood waste from pulp production	[56]
Corn residue (<i>Z. may</i>)	-	790	9.2	-	6.7	600	Soil plowed upto 0.1–0.12 m depth for maize (<i>Zea mays</i> L.) cultivation without fertilizer application	[57]
Green waste	6.2	680	1.7	0.2	1	450	Green waste biochar having mixture of a grass clippings, cotton trash, and plant prunings	[58]
Pecan shell (<i>Carya illinoensis</i>)	7.6	834	3.4	-	-	700	Feedstocks are commonly produced as agricultural byproducts and available in large quantity	[59]
Pecan shell (<i>C. illinoensis</i>)	-	880	4.0	-	-	700		[60]
Poultry litter	9.9	380	20	25	22	450	Cover of poultry farm litter used to prepare biochar	[58]
Poultry broiler litter	-	258	7.5	48	30	700		[52]
Poultry broiler cake	-	172	6.0	73	58	700		[52]
Rice husk (<i>Oryza sativa</i>)	9.5	48	10	15	20	650–700		[61,62]
Sewage sludge	-	470	64	56	-	450		[63]
Vine shoots (<i>Vitis vinifera</i> L.)	8.6	715	14	20.8	17	400	Prepared in a fixed-bed laboratory reactor having cylindrical and vertical reactor made with stainless steel	[64]
Wood (<i>Eucalyptus deglupta</i>)	7.0	824	5.7	0.6	-	350		[65]
Wood (<i>Pinus ponderosa</i> , <i>Pseudotsuga menziesii</i>)	6.7	740	16.6	13.6	-	Wildfire	Hardwood has been used to prepare the biochar which is considered.	[66]
Wood (<i>Quercus</i> spp.)	-	759	1.0	-	1.1	350		[57]
Wood (<i>Quercus</i> spp.)	-	884	1.2	-	2.2	600		[57]

After detailed investigations of different physical and chemical parameters of biochars, it was found that biochars produced using woodchips (high lignin content) as a feedstock had a higher C:N ratio and larger surface area when compared with dairy manure biochar produced at the same pyrolysis temperature [67]. The studies on different biochars, including pecan shell, poultry litter, switchgrass, and peanut hull have shown significantly different properties of the resulting product. Poultry litter biochar showed higher Ca and Mg contents, resulting in higher pH values, and pecan shell biochar demonstrated the highest surface area due to its high intrinsic density [59]. The feedstock's composition and moisture content could affect the pyrolysis products yield [54]. The fast pyrolysis process generally requires dry feedstock so that moisture content will not restrain the high temperature effect through evaporation. However, the slow pyrolysis process is much more tolerant to high feedstock moisture. Feedstock particle size can also have a significant effect on the yields of char and liquid products. Feedstock with bigger particle size produces more char by reducing the first stage products' evaporation rate, which increases the possibility for secondary reactions [54,68].

4. Properties of Biochar

The biochar has various properties, mainly depending on the feedstock type and the pyrolysis conditions. The biochar properties are governed by its composition, stability, specific surface area, pH, cation exchange capacity (CEC), porosity, decomposition capability, and contaminants level. However, the chemical composition, available nutrients, and the level of contaminants of biochars mainly depend on the composition of the used substrates/feedstock. Biochar is considered alkaline in nature and mainly has a pH > 7.0. The soil has a strong buffering capacity (resistant to changes in pH), and in case of soil with a pH > 7.5, the biochar should not be applied frequently as it may impair the fertility and nutrient availability of soils. Biochar is mainly recommended for soil that has acidic pH and low content of organic carbon. It has been reported that biochar could enrich the soil systems with divalent cations. The addition of biochar to saline-sodic soil could be a source of Ca^{2+} and Mg^{2+} and mainly responsible for salt leaching [69]. It has been reported that the application of biochar increased the yield of *E. viminal* when grown in saline sodic soil.

Most biochars prepared from crop residues tend to exhibit neutral to alkaline properties depending on pyrolysis temperatures [70,71]. The rise in pH in biochar derived from sugarcane straw, poultry litter, corn straw, pine, and sewage sludge were reported with the increase in pyrolysis temperature [23,72]. The changes in pH values depend on non-pyrolyzed inorganic elements of feedstocks, pyrolysis temperature, and production duration [59]. The elevation in pyrolysis temperature could also enhance biochar specific surface areas due to micropores development (Table 1). The long-term stability of biochar plays a major role in carbon sequestration. It can be achieved in a wide range of production conditions [34].

The literature summarized the minimum and maximum values of biochar properties as follows: pH: 4.5–12.9; electrical conductivity (EC): 20–10,260 mS cm^{-1} ; cation exchange capacity (CEC): 3.8–272 cmol (p+) kg^{-1} ; surface area: 0.1–410 $\text{m}^2 \text{g}^{-1}$; bulk density: 0.05–0.7 Mg m^{-3} ; volatile matter: 0.6–85.7%; K: 0.3–74.0 g kg^{-1} ; P: 0.005–59 g kg^{-1} ; Ca: 0.04–92 g kg^{-1} , Mg: 0.009–37 g kg^{-1} ; C: 17.7–92.7%; H: 0.05–5.30%; O: 0.01–39.2%; H/C: <0.01–1.14; O/C: 0.02–1.11 [73–77].

The source of organic and inorganic contaminants in biochar is an issue of major concern. Some of these contaminants may be generated and simultaneously destroyed during the process itself, but some will remain unchanged or converted into more harmful substances. However, heavy metals present in the feedstock remain unchanged and concentrate in the biochar [78,79]. The contaminants that form during pyrolysis are represented by polycyclic aromatic hydrocarbons (PAH) and dioxins [80]. PAHs can be formed during the pyrolysis process at high temperature during secondary and tertiary reactions [81]. With the rise in temperature, pyrolysis severity rises, and PAHs production becomes significant at around 750 °C. It was found that the concentration and composition of PAHs in biochar are feedstock-dependent to some extent [82]. The detailed information on contaminants in biochar and its application to agricultural soils is added in Section 6. The biochar application improves soil physical qualities, i.e., improve aeration, water holding capacity, enhance porosity, and reduce the evapotranspiration and bulk density of soil [83–85].

Biochar exhibits a high surface area, the presence of pores, and different functional groups hydroxyl (-OH), carboxylic acids (-COOH), and small alkyl chains such as methane groups (-CH₃) [86,87]. These attributes increase the nutrient retention capacity of biochar, even of the negatively charged NO_3^- and PO_4^- ions [87–89]. The pores of biochar serve as a secure habitat for microorganisms [90–92] such as bacteria (size range from 0.3–3 μm), fungi (2–80 μm), and protozoa (7–30 μm); these pores protect them from predatory microarthropods [93]. Biochar macropores (>200 nm) are the most protective habitat for bacteria because of the similar size, although biochar can store water and dissolved substances in micropores (<2 nm) and mesopores (2–50 nm) [86]. The size of the pores depends on the temperature of biochar production. At higher temperatures, pore size will be larger due to more water and organic matter volatilization [86]. It was reported that biochar produced at 500 °C using 5 feedstocks in 600 × 500 μm SEM image sugarcane bagasse,

paddy straw, and umbrella tree wood biochars had mostly 10–50 μm , 20–100 μm , and 50–70 μm diameter pore sizes, respectively [94]. In $60 \times 50 \mu\text{m}$ SEM images, cocopeat husk and palm kernel biochars showed 5–10 μm and 1–3 μm diameter pore sizes, respectively. The size of the pores in a biochar can also depend upon the plant part used [95]. The size and diameter of vessels increases along with decreases in density from leaves to roots.

5. Impact of Biochar on Soil Properties

There is plenty of evidence that biochar helps to improve the physicochemical and biological properties of soil, which are essential for crop production (Figure 2; Tables 1 and 2).

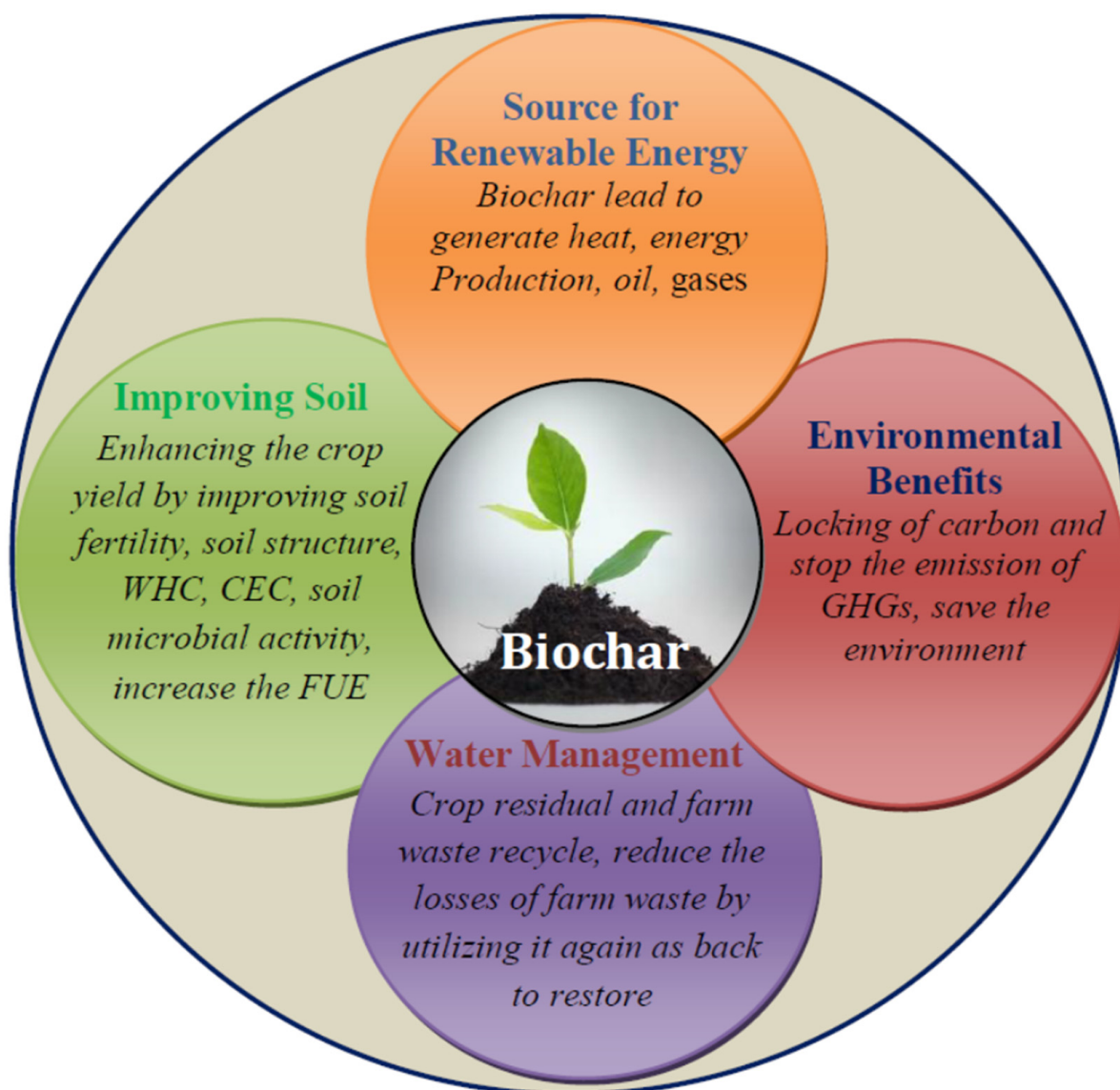


Figure 2. Potential components of biochar for sustainable management in agriculture sector.

Table 2. Effect of different types of biochar on crops yield.

Biochar Type	Application Rate of Biochar	Experimental Crop	Soil Type	Experiment Years	Country	Type of Experiment	Examined Depth of Soil	Major Finding	Remarks	Reference
Charred bark of <i>Acacia mangium</i>	10 L m ⁻² (Char-NPK)	Maize, cowpea, and peanut	Acidic soil	1	Indonesia	Field	10 cm	Acacia bark charcoal plus fertilizer increased maize and peanut yields (but not cowpea).	Bark of <i>Acacia mangium</i> (charred) shows significant improvement in crop yield with potential improvement in soil.	[56]
Charcoal <i>Eucalyptus deglupta</i>	0, 30, 60, and 90 g kg ⁻¹ soil	Bean	Clay-loam oxisol	1	Colombia	Greenhouses/Pot	0.2 m	Bean yield increased by 46% and biomass production by 39% over the control at 90 and 60 g kg ⁻¹ biochar, respectively.	Hardwood material has been used to prepare <i>Eucalyptus deglupta</i> biochar.	[65]
Charcoal with chicken manure	4.7 to 0 mg kg ⁻¹	Rice and Sorghum	Xanthic Ferralsol	2 crops Long Term	Brazil	Field	0–0.1, 0.1–0.3, and 0.3–0.6 m	Charcoal amended with chicken manure amendments resulted in the highest cumulative crop yield.	Waste of chicken manure has been used as experimental material, and it shows potential improvement.	[96]
Charcoal	6 t C ha ⁻¹	Maize	Ultisol	1 crop Long term	Kenya	Field	0.1 m	Doubling of crop yield in the highly degraded soils from about 3 to about 6 ton ha ⁻¹ maize grain yields.	Shows significant improvement in crop yield and soil.	[97]
Wood	0–4% w/w	Corn	Wahiawa and Khorat soil	1	Thailand	Pot	-	Decrease biomass in first season and increase in biomass in second season.	Pine wood has been converted into biochar through pyrolysis and shows a significant yield improvement.	[98]
Wood	0–50 wt. %	Oats	Sandy and loamy	1	Germany	Pot	-	Increase in grain yield.	Rice husk biochar has been collected from mills, which is considered as waste material.	[99]
Wood	0–25 tha ⁻¹	Maize	Light clay	1	Australia	Field	0–12 cm	Increase grain yield 8–29%.	Hardwood of the plant has been used to prepare the biochar which shows are considered.	[100]
Wood	0–20 tha ⁻¹	Maize	Clay loam	4	Colombia	Field	0–30 cm	Increase grain yield 0–140%.		[88]
Wood	0–25 tha ⁻¹	Maize	Light clay	1	Australia	Field	0–12 cm	Increase grain yield 13–29%.		[101]
Straw	0–40 tha ⁻¹	Rice	Entic Halpudept	2	China	Field	0–15 cm	Increase grain yield 9–28%.	Straw has been used to prepare the biochar and shows significant improvement in Ca-enriched soils (composed of calcium carbonate).	[102]

The application of biochar is more effective for soils with low OC content and low soil pH. The application of biochar to the soil results in better aeration and higher water holding capacity, porosity, nutrient holding capacity, and microbial population [62,84,85,99,103]. This section mainly focuses on how biochar amendment could influence different soil properties, especially pH, EC (Electrical Conductivity), CEC (Cation Exchange Capacity), O:C ratio, NPK, soil organic matter, and soil biological activity.

5.1. Soil Physicochemical Properties

The literature reported increases in soil pH after applying various types of biochar [104,105]. The alkaline biochar addition could increase acidic soils' pH by 0.1 to 0.2 units [106]. However, at high biochar application rates, acidic soil's pH could rise up to 2.0 units [107]. The biochar application is mainly recommended based on the properties of soils. The soil with low OC content, acidic pH, and poor soil physical properties has the most effective response to biochar. The buffering capacity of the soil generally resists the change of soil pH. There are some other reasons for an increase in soil pH after applying biochar such as the activity of negatively charged phenolics, carboxyl, and hydroxyl groups on biochar surfaces. These groups bind H^+ ions present in the soil solution and reduce their concentration in the soil solution, resulting in the rise of soil pH value. This feature can be vital to decreasing the uptake of contaminant by crop plants, as the plants possess H^+ efflux pumps and the root exudates are acidic in nature. Simultaneously, too-high soil pH could lead to adverse effects, such as reducing phosphorus, magnesium, and molybdenum bioavailability.

The application of biochar to soil could alter soil EC and CEC. The EC value of soil increases due to the elevated concentration of soluble salts in biochar [108,109]. A sudden increase in EC from 0–2 dS/m may have a harmful effect on the soil due to extensive accessibility of soluble salts, which increases the osmotic pressure of soil solution, resulting in a reduced availability of water and nutrients from the soil. Alteration in soil CEC after the application is a collaborative effect of biochar's feedstock, pyrolysis temperature, and biochar degradation in soil. Application of wood biochar increases the CEC of soil to a more considerable extent than crop residue biochar [110]. This increase in CEC of soil may be due to the oxidation of specific functional groups such as phenolic, carboxylic, lactone, pyranone, and amine on the biochar's surface [111]. Biochar behaves as a cation exchange resin that may retain or exchange different cationic species [11,112]. It also increases soil CEC and helps in long-term carbon sequestration [113]. Increased plant growth followed by increased crop productivity are a possible response to increased CEC [58,114].

The wood-based biochar has a longer-lasting effect due to more carbon and being more resistant to decomposition in the environment. Such products have a potential capacity to sequester the carbon in the soil for a very long time. The dry wood may be converted to biochar before decaying and can be potentially used for energy and soil improvement [115]. Different properties of biochar such as the surface area and O:C ratio are also important in understanding the biochar interaction with organo-mineral complexes, i.e., the first step of aggregate formation and stabilization. The main electron shuttling and redox-active moieties are quinones, which are responsible for the two-way direct linkage between mineral or organic surfaces or the indirect linkage through a non-biochar organic matter cross-linking agent that binds biochar to mineral surfaces in a three-way linkage [116,117].

Biochar produced with slow pyrolysis (400–600 °C) has a positive influence on soil aggregation in a wide variety of soils [118–120]. However, biochar produced at high temperature (700 °C) with a low O:C ratio did not show any significant results [60], which may be because of the lower amount of organic matter content in this biochar. It was found that straw derived biochar increased soil macroaggregate by 17.77–18.87% and 33.55–50.87% in 0–20 and 20–40 cm soil layers in a rice–wheat rotation system, respectively [121].

Biochar is known for its potential in carbon sequestration along with considerable improvement in soil functions [61]. The application of rice husk biochar increased the carbon content in soil due to its recalcitrant nature [11,122]. Thus, the biochar could stabilize soil organic matter and increase respiration and decomposition [123].

Biochar contains many carbonaceous compounds that are useful for improving soil fertility [33,124–126]. The various types of biochars contain high percentages of carbon, for example, in chicken manure-derived biochar contains 51.7% C and green waste-derived biochar contains 77.5% C when prepared at 550 °C [123] and 70–85% from the wood of different tree species, depending on the pyrolysis temperature [127,128]. The lowest percentages of carbon (29–50%) were found in rice husk and straw as compared to woody biochars [128]. Organic matter, inorganic salt, and humic substances such as humic acid, fulvic acid, and humin can serve essential functions in plant nutrition [39]. The biochar produced from *Acacia saligna* at 380 °C and sawdust at 450 °C contained humic-like (17.7%) and fulvic-like (16.2%) substances [127].

The application of biochar to soil might address the problem of climate change and also improve soil fertility. However, the positive priming of biochar on the decomposition of native soil organic matter and the abiotic release of CO₂ from the reaction of carbonates in the biochar after the amendment to acidic soil were identified [129,130]. The main source of the increase in CO₂ emissions from a biochar amended soil seems to be microbially mediated decomposition of labile biochar constituents [131,132]. The CO₂ emission in biochar-applied soil appears to be a short-lived effect [133].

The long-term effects of biochar presence in soil are still unknown because it can persist in soil over centuries. Systematic biochar work in the soil to sustain the soil health over a long time has been depicted in Figure 3 and the fate of biochar application in the soil to renovate various soil properties has been presented in Figure 4.

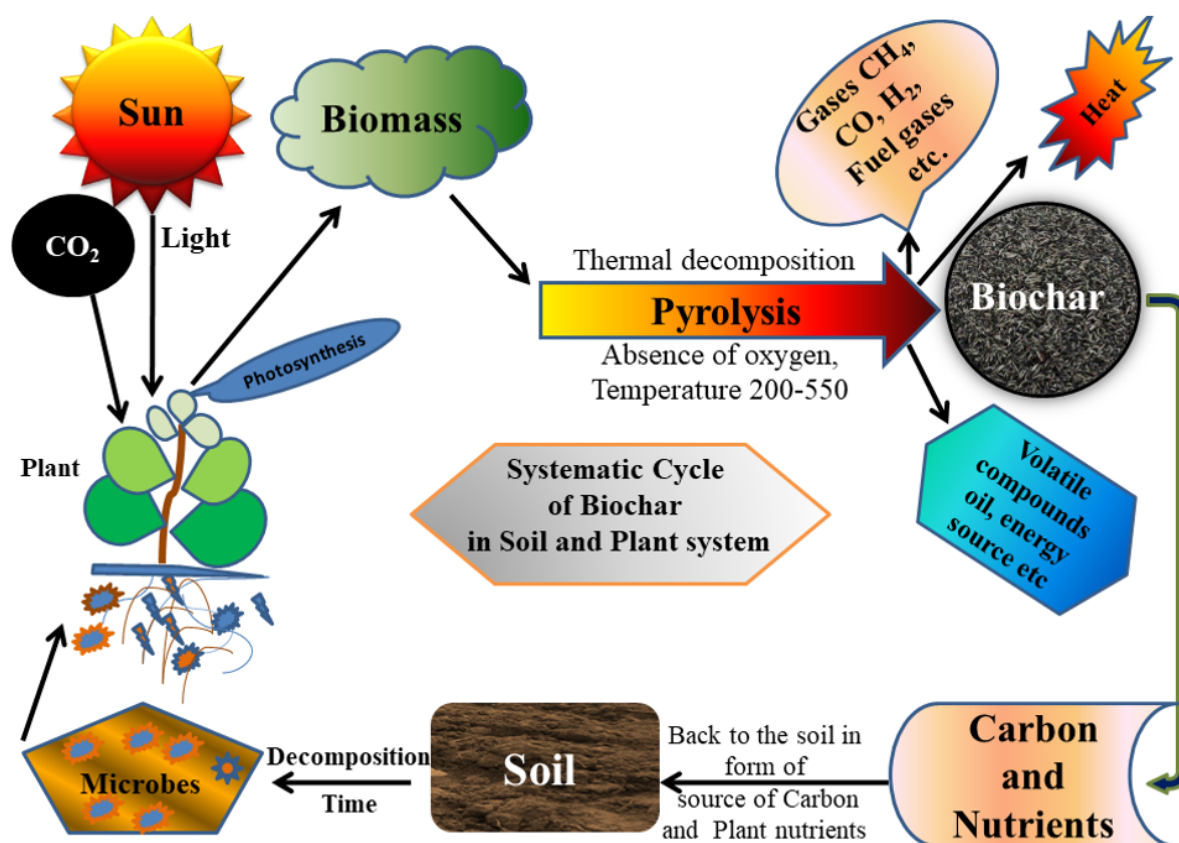


Figure 3. Systematic biochar work in the soil to sustain the soil health prolongs time.

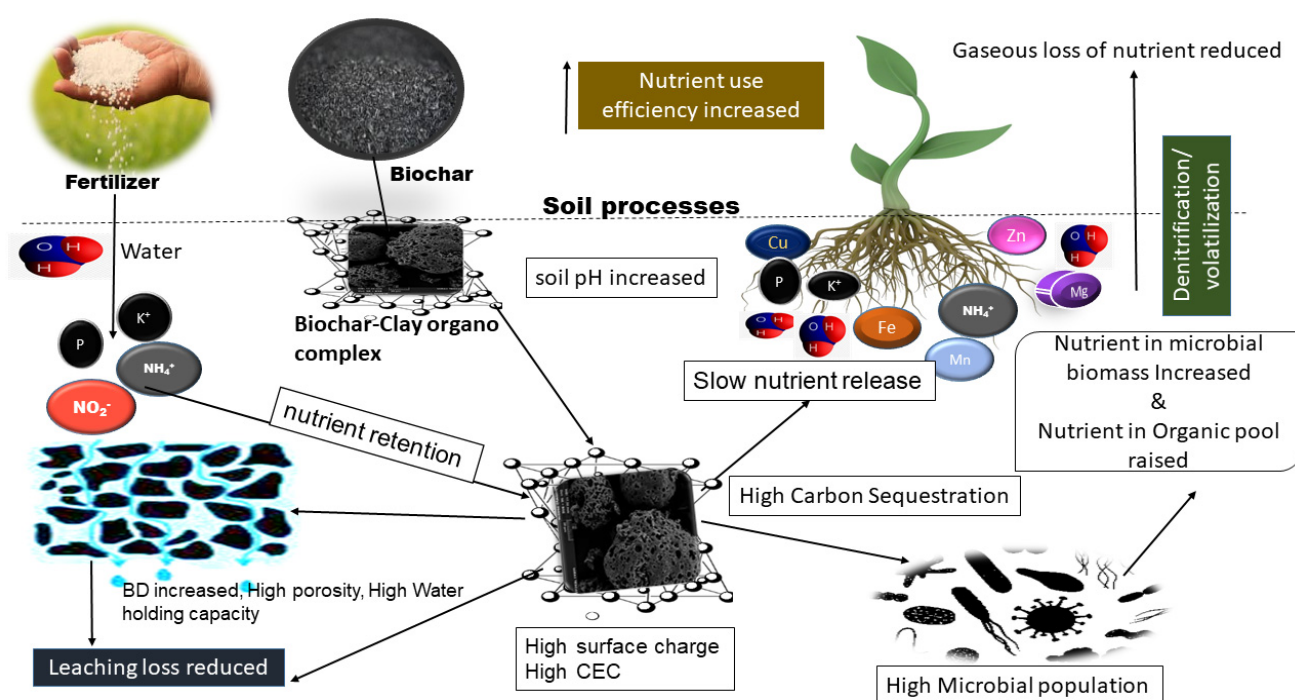


Figure 4. Fate of biochar application in the soil to renovate various soil properties.

5.2. Soil Biological Properties

Biochar has a profound influence on soil biological properties. The mechanisms of this influence are diverse and can be both direct and indirect through the alteration of soil properties after the application of biochar. Direct mechanisms include the influence of biochar on soil microorganisms, which can be positive and negative.

The positive influence of biochar on soil microorganisms includes creating a new habitat for colonization due to biochar's porous structure [134,135]. Pore size has a significant effect on the pace of biochar colonization by the microorganisms: larger pores are colonized more rapidly, but they do not provide a shelter for soil microfauna [136]. The aging of biochar is also important for microbial colonization. Fresh biochar releases organic substances that microorganisms can utilize as a carbon source, supporting the bacterial growth and promoting colonization [137]. At the same time, fresh biochar can release toxic substances, and it has been demonstrated that aged biochar increases soil microbial activity, while fresh biochar suppressed it [138]. Another positive effect on microorganisms is that biochar can serve as a mineral nutrient source that can originate from pyrolyzed ash or concentrated on the biochar surface through sorption from soil solution. The enhanced microbial activity can also be connected with the increased CEC from biochar application [134,139]. Biochar granules are also capable of holding water that positively influences the microbial communities and allows them to recover more quickly after the commencement of drought conditions [139].

The incorporation of biochar amendments can stimulate the growth and development of plants, along with significant improvement in microbial populations [140], and can also affect the abundance of microbes (bacteria, ratio of fungi, community structure) [141–143].

Azeem et al. [144] reported that the sole application of biochar does not influence (non-significant) on microbial population, while compost alone and with the conjoint use of biochar significantly boosts the enzymatic activity. They also reported that the application of 5 cm green waste compost and of 12.5 t ha⁻¹ biochar and 5 cm compost resulted in 6%, 54%, and 54% increases in urease, dehydrogenase, and β -glucosidase activity, respectively, as compared to a control. It was also reported that green waste compost (5 cm) and 12.5 t ha⁻¹ biochar and 5 cm compost significantly improved the

fungus and bacterial respirations by 426% and 346% and 88% and 161%, respectively, compared to the control soil.

In a recent study, it has been shown that the metabolic activity of the soil microbial communities increases when biochar is applied in drought conditions, and the aging of biochar increased its positive effects [145]. However, biochar can also exhibit suppressive effects on the soil microbial communities, and these effects largely depend on the feedstock, pyrolysis conditions, and the mode of biochar application. The adverse effects on microorganisms originate from byproducts of pyrolysis, such as volatile organic compounds (VOCs) and PAHs. The majority of studies report strong toxic effects of VOCs: the inhibition of nitrification [26], suppression of *Bacillus mucilaginosus* [146], and toxicity to *Cyanobacterium Synechococcus* [147]. The influence of biochar on soil microorganisms has been summarized in several recent reviews [135,148].

The incorporation of Co-biochar into the soil not only significantly increased growth and development but also the microbiota and the enzymatic activity (Azeem et al. 2019). It was noted that the incorporation of biochar amendments could enhance plant growth as well as microbial populations (bacteria, ratio of fungi, community structure, enzymatic activity) [16,144,149,150]. Recently, it was also observed that the combined application of wheat straw and wheat straw biochar improves soil's physicochemical and biological properties [149]. Other authors found that the co-application of wheat straw and of wheat straw biochar with the addition of nutrients at 1% and 2% doses significantly increased C and N contents in soil along with their dissolved organic carbon and dissolved organic nitrogen, post-harvest soil properties, i.e., pH value and C and N content, and concluded a positive effect of biochar and nutrients application on the microbial population in soil. It was also noticed that green waste compost (5 cm) and 12.5 t ha⁻¹ biochar and 5 cm compost significantly improved the respiration (i.e., fungus—426% and 346%; bacterial—88% and 161%) compared to the control soil [144]. The addition of biochar on the organic fraction of municipal solid waste (OFMSW) in real conditions found significant changes in carbon, nitrogen, organic matter, respiration activity, moisture content, as well as the microbiocenotic composition of microorganisms [151]. This addition of biochar reduced the compost toxicity and retained nitrogen during composting but did not appear to increase the rate of composting, enhance the moisture %, lower waste density, retain N, or lower the pathogenic microorganisms during the composting. During composting, the maximum abundance of mesophilic bacteria (1704.5–2198.1 10⁴ CFU g⁻¹ d.m.), endospores bacteria (84.9–298.9 10⁴ CFU g⁻¹ d.m.), and actinomycetes (0–19.5. 10⁴ CFUg⁻¹ d.m.) were found after 7 days of composting with the addition of biochar [151].

Biochar can also influence soil enzymatic activity by various mechanisms. Firstly, the impact on soil biota influences the synthesis of enzymes and their release into the soil. Secondly, the shifts in pH can both stimulate and inhibit the existing enzymes. Thirdly, the enzymes can be directly adsorbed by biochar particles, influencing their activity [152]. Dehydrogenase activity with the addition of wheat straw, wheat straw biochar, and nutrient addition was 1.6–4-fold higher compared to the control in soil [149]. However, the sole application of biochar did not influence the soil microbial population, while compost alone and in conjunction with biochar significantly boosted the enzymatic activity. The application of 5 cm green waste compost and 12.5 t ha⁻¹ biochar and 5 cm compost showed 6%, 54%, and 54% increases in urease, dehydrogenase, and β -glucosidase activity, respectively, as compared to control [144].

Several other mechanisms can be involved, including the adsorption of metal ions, limiting the metalloenzymes activity, generating reactive oxygen species (ROS) that can inactivate the enzymes, and others. Due to the involvement of many different mechanisms, the impact of biochar on enzymatic activity is somewhat controversial. Different reactions were demonstrated for various soil enzymes following the biochar application. For example, biochar application increased soil urease activity, which may be attributed to the increased pH of soil solution [153]. Simultaneously, the β -glucosidase and β -glucosaminidase activities were decreased when biochar produced at 300–550 °C was applied [154].

To conclude, the biological properties of soil are altered by the addition of biochar to a great extent, and the type of biochar determines whether this effect will be positive or negative. Many adverse side effects of biochar can be avoided if the biochar is aged or co-composted before its application to the agricultural soil.

6. Opportunities and Challenges of Biochar Application to Agricultural Soils

During the process of pyrolysis, several organic pollutants such as PAHs, dioxins, or furans are produced, and the metals present in contaminated feedstock become concentrated after pyrolysis [155]. Thus, biochar application to the soil for cultivating crops may pose a potential threat to human and livestock health. Therefore, appropriate risk management practices should be followed when biochar is used in the crops or pastureland. The application of biochar and ash produced from biomass can be a complementary option to traditional mineral fertilizer and may help strengthen the ecological aspect of agro-energy [156]. Certain issues need to be taken into account while considering biochar as a soil amendment. The absorption of metals by biochar may lead to decreased bioavailability of essential micronutrients in the soil. However, in due course of time, the potential metals might be taken up by the plants. Hence, biochar should be used more specifically taking soil properties into account.

7. Organic Contaminants

Due to its high sorption capacity, biochar is effective in the sequestration and adsorption of organic contaminants [21]. The increases in the sorption of organic contaminants could decrease other contaminants' bioavailability [157]. The sorption is somehow beneficial in reducing toxic effects and the transfer of hydrophobic organic compounds (HOC), such as PAHs to the food chain. It was found that biochar enhances the lifetime of contaminants in the soil by decreasing their mineralization rate [158]. On the other hand, the degradation rates increased after biochar amendment, this may be because of biochar's ability to reduce immediate toxicity of freshly peaked contaminants to soil microbes [159]. If the bioavailability of contaminants is not a controlling factor, biochar amendment to soil can help reduce the risks of overloading the biodegradation capacity of soil [160,161]. It is concluded that the application of biochar in soil raised the PAH levels by 0.02–3574 $\mu\text{g kg}^{-1}$ [162]. This concentration is sufficient to contaminate the food which is grown in this type of soil.

Although biochar has a high sorption capacity, it is still not always helpful in reducing the leaching of hydrophobic organic compounds (HOC). It could even increase the HOC leaching risks if biochar releases a considerable amount of dissolved organic carbon [90]. The amount of dissolved organic carbon decreases with increase in biochar pyrolysis temperature, and release is also lower if the feedstock is hardwood material rather than grasses [84]. It was recommended that the use of woody feedstock and slow pyrolysis at a higher temperature (500–600 °C) could be helpful to maintain the lower PAH and dioxin concentration in biochar [80]. Therefore, the careful selection of the feedstock and pyrolysis condition is needed to reduce HOC pollution risk when using biochar as a soil amendment.

8. Inorganic Contaminants

Biochar is considered a very effective tool in removing inorganic contaminants from polluted soils and waters. Industrial wastewater bears metal concentrations at lower levels, which cannot be adequately removed while using reverse osmosis, ion exchange resins, electrolysis, electrolytic recovery, coagulation, etc., and using biochar can serve this purpose [163]. The scots pine and silver birch biochar efficiently eliminate heavy metals present in contaminated water [164]. To conclude, biochar is a cheap and effective sorbent for the treatment of contaminated waters. The recent advances in biochar application in water treatment have been reviewed in several recent articles [165–168]. Most of these studies have discussed the effects of biochar properties on the efficiency of contaminant removal from the polluted waters, and the possible modifications of biochars to further

enhance their adsorption efficiency and capacity. Unlike the use of biochar for wastewater treatment, its application to soil is a more complex problem because the sorbent cannot be removed, and thus, the long-term effects on soil physicochemical and biological properties should be thoroughly considered.

In recent years, the studies on biochar application in soils polluted with heavy metals (HM) have been summarized in several scientific reports [168–170]. Biochar has an adsorption capacity for heavy metals due to its increased negative surface charge and area [171,172]. The mechanisms of biochar detoxification of the HMs in soils mainly involve immobilization due to electrostatic interactions, cation exchange, and adsorption, reducing them to less toxic forms [173]. The organic matter content in biochar may be used to increase the immobilization of HMs in polluted soils due to the electrostatic and non-electrostatic forces [174].

Despite the benefits from applying biochar to contaminated soils, there are also concerns regarding biochar as a possible source rather than a sink of pollutants. These concerns are raised because biochar is considered not only for remediation of polluted soils but also for agricultural soils and possibly a global carbon sequestration tool. This implies large scale production and application of biochar to the soils. The main source of inorganic contaminants in biochar is the feedstock that is used for its production.

Feedstock for biochar (e.g., sewage sludge or preservative-treated waste wood) may contain a large amount of HMs (e.g., Pb, Ni, Cu, Zn, and Cr), which are not volatilized during pyrolysis and metal enrichment of biochar cannot be avoided. It was concluded that wood containing a small amount of preservative can impose a risk to soil quality as well as crop production if used as feedstock for biochar preparation [175]. Feedstock used for biochar and the pyrolysis process are responsible for the concentration of micro- and macro-elements in biochar [176]. Following the application of metal-contaminated biochar, the toxic elements can enter the soil solution and be taken up by the crop plants. The concentration of metals in biochar could be high, but they may be less bioavailable to plants due to the strong adsorption of feedstock-derived metals on the charred material. Therefore, the feedstock quality needs to be critically examined before the preparation of biochar so that the pollutant load can be avoided prior to its use as a soil amendment [177].

9. Biochar and Human Health Risks and Benefits

The application of biochar has a significant impact on the soil as well as on the environment if applied precisely. During the biochar preparation, there are some issues that may impact the human health significantly. As the finding shows that inhalation of the small biochar particles during its preparation, incorporation, or due to wind erosion can cause serious respiratory disease known as pneumoconiosis [178]. The elevated metal concentrations present in biochar increased human health risk [179]. It can irritate eyes and mucous membranes by airborne pollutants on biochar particles [180]. So far, if the biochar application is considered in a large area, it should be used precisely in soil by following the specified precautionary measures. The possible contaminants present in biochar leach through the soil and enter groundwater. They are accumulated by soil organisms and biomagnified through food webs, which cause toxicity at higher levels. However, the maximum health risk could be encountered by consuming crop plants that have accumulated large amounts of metals in their edible parts, especially root crops, if grown in contaminated soils. Biochar is an efficient sorbent and can reduce the uptake of heavy metals by crop plants grown in contaminated soil. Owing to their sorption properties, it can effectively immobilize contamination from solid, liquid, and gaseous media. It has been shown that the application of biochar can reduce nitrates level in red beet [181]. Biochar also reduces greenhouse gases emissions (N_2O , CH_4) from agricultural soils and improves soil fertility. It has been reported [182] that the application of biochar could offset a maximum of 12% of anthropogenic greenhouse gases emissions on an annual basis. The reduction of greenhouse gas emissions also has a long-term influence on human health globally.

10. Conclusions

The present review reveals that biochar helps to improve soil physical, chemical, and biological properties. It also contributes to addressing critical environmental issues such as greenhouse gases emission from soil. Biochar generally exerts a positive influence on all soil types, but there are certain soil properties which restrict its application. The possible factors which limit the use of biochar as an amendment are the type of biochar, the production conditions, the soil properties, and the amount of biochar applied. Similarly, the presence of heavy metals, organic contaminants, and other pollutants in biochar are among the serious issues that need to be taken in to account during the production of biochar by providing the proper pyrolysis conditions and choosing the suitable types of feedstocks. Considering all the aspects and importance of biochar, it is concluded that biochar has a potential role in sustainable soil management. Moreover, biochar also helps to manage the soil and the environment in a sustainable and eco-friendly way. Studies are required to be conducted on different types of soils and the availability of heavy metals. As biochar is rarely applied in arid and semi-arid soil due to high soil pH, it is necessary to assess the potential risks and benefits of biochar application to such soils. The commercialization of biochar also requires it to be promoted for further use in sustainable application. More studies should be taken up on biochar to explore its potential use in the years to come.

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